# Single-Slit Diffraction of Neutrons*

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Observations are reported on single-slit diffraction of monochromatic slow neutrons (wavelength 4.43 Å) upon passage through fine slits of width between 21 and 4.1 $\mu$. Gadolinium-edged slits were used because of the high-absorption cross section for this material, and the angular broadening effects in the range up to 20″ of arc were studied on a high-resolution double-crystal spectrometer utilizing perfect crystals of silicon. The observed broadening agrees well with that calculated, and this supplies evidence on the width of the coherent wavefront of a neutron wave packet.

THE Heisenberg uncertainty principle stipulates that a transverse momentum uncertainty is introduced when a particle is passed through a slit opening. Alternatively, this can be portrayed as single-slit diffraction of a de Broglie wave packet, and within the limits of the uncertainty relation, the two approaches agree quantitatively. Direct experimental observation of this broadening is of course historic in the case of photons. The present note presents similar observation for the case of neutron wave packets passing through fine slits.

On a diffracted wave model the Fraunhofer single-slit diffraction pattern is described by the intensity $I(\beta)$ at deflection angle position $\beta$ by

$$I(\beta)=I_0\frac{\sin^2[(\pi a/\lambda)\sin\beta]}{[(\pi a/\lambda)\sin\beta]^2} \quad (1)$$

with $a$ the slit width and $\lambda$ the wavelength. The dominant central intensity peak has its half-intensity angular position at $\sin\beta_{1/2}=0.444\lambda/a$ and its first zero intensity position at $\sin\beta_0=\lambda/a$. With slow neutrons of 5 Å wavelength passing through a slit of width 10 $\mu$, the deflection angles are of the order 10″ of arc and high resolution is called for in observing this. This angular resolution was obtained in the experiment by using a double-crystal spectrometer with perfect crystals of silicon both in (111) Bragg reflection as shown in Fig. 1. In such parallel orientation, the rocking curve of the second crystal (variation of its reflected intensity with orientation angle) is very narrow and is independent of collimation present in the system. This angular sharpness is available in spite of the wavelength band (in practice about 1%) that is passed through the system because of the near-perfect dispersion that characterizes the beam between the crystals. If any angle broadening or deflecting agent is placed between the crystals, the rocking curve will be very sensitively affected. Thus a test slit of fine dimension placed between the crystals will be expected to broaden the normal rocking curve of the system.

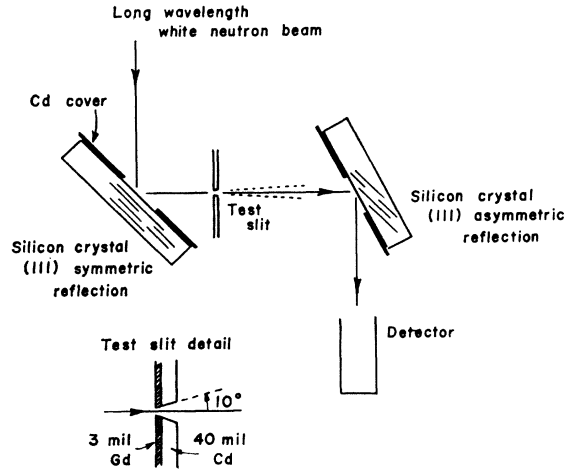


FIG. 1. Diagram of double-crystal spectrometer used in establishing the single-slit broadening of neutron wave packets. The inset diagram shows detail of the slit construction.

In the experiment, the crystal spectrometer was positioned in a long-wavelength neutron beam which had passed through a cooled Be filter, reflected from a curved Soller slit system of nickel sheets and finally passed along an extended pipe channel.[1] This procedure supplies a white neutron beam (intensity about $10^7$ neutrons/cm$^2$ sec) with wavelengths longer than 3.96 Å (the Be transmission cutoff) and a minimum of contaminant $\gamma$-ray and more-energetic-neutron intensity. From this spectrum the first crystal selects a wavelength band centered at 4.43 Å by Bragg reflection through a scattering angle of 90°. This beam is again reflected by an equivalent set of planes in the second crystal, spaced 35 cm from the first, into an open detector. Very fine angular orientation control is necessary in the second crystal mount for scanning over the narrow rocking curves, and this has been accomplished with a torsion-bar goniometer similar to that described previously.[2] The angular calibration of the goniometer system was obtained with a sodium-light interferometer assembly.

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[1] This beam pipe facility was designed and used by R. Nathans and the author is indebted to him for its use in these experiments.

[2] C. G. Shull, K. W. Billman, and F. A. Wedgwood, Phys. Rev. 153, 1415 (1967).

Cadmium shield cover plates of width 8 mm were placed on the front surfaces of both crystals. These cover plates prevent emergence of back-face reflected intensity from the crystal plates and thus reduce the rocking width somewhat.[3] Additionally, an asymmetrically cut crystal was used at the second axis, and this also served to narrow the rocking curve.

Details of the test-slit construction are shown in the inset of Fig. 1. A 3-mil-thick sheet of Gd metal was cemented to a heavier base of Cd and two faces of one corner were surface-ground with a bevel angle of 10° leaving an exposed Gd edge of 80° internal angle. Two such edges (Gd) were brought together with a residual opening which was to serve as the slit width. The bevelling of the inside surfaces insured that the same slit width was being sensed by all of the rays travelling through the opening. Moreover, the bevel angle was sufficiently large that no total reflection of neutron rays on the inside surface could occur. Preliminary studies were carried out with plain Cd edges, which showed the presence of prism action on rays which were seeping through the partially transparent Cd edges. The Cd absorption cross section (4500 b at this wavelength) is not high enough to prevent this, and for a very small slit width, the edge leakage intensity may be comparable to the transmitted intensity. Accordingly the Gd-Cd assembly was used with the much more highly absorbing Gd (100 000 b) serving as the critical edge material.

The diffraction broadening produced by three different slits of width 21.0, 5.6, and 4.1 $\mu$ was studied. These slit-width values were established in two different ways by neutron measurements: (1) The slit was placed ahead of the first crystal, and the transmitted intensity measured in the double-crystal assembly was compared with that transmitted through a set of larger slits whose widths could be measured optically; and (2) the integrated intensity in the rocking curves was compared with that of larger calibrated slits. The results obtained by the two methods agreed satisfactorily with each other. Determining the slit width by neutron measurements automatically gives an effective width more closely related to the diffraction broadening than a width determined by optical means if edge transmission effects are present. In the diffraction-broadening experiments, the test slit (of height 15 mm) was positioned between the crystals at a distance 5 cm from the first-crystal reflecting face.

Figure 2 shows rocking curves for three slits, a very large one and two fine ones. The curve for the large slit, for which diffraction broadening is unmeasurable, serves to give the instrumental width of 6.10″ arc as the width at half-maximum intensity.[4] This instrumental width

TABLE I. Observed and calculated diffraction broadening of neutron rays by single slits.

| Slit-width ($\mu$) method (1) | method (2) | Observed half-width (seconds arc) | Corrected experimental diffraction width (seconds arc) | Calculated diffraction width (seconds arc) |
|---|---|---|---|---|
| 21.3 | 20.6 | 7.74 | 4.5 | 3.9 |
| 5.2 | 6.0 | 15.4 | 14.5 | 14.5 |
| 4.2 | 4.0 | 20.8 | 19.9 | 19.8 |

was established as being independent of slit width for large slit opening. The smaller slits show a considerable broadening with measured half-widths of 15.4 and 20.9″ arc. Because the intensity passing through the fine slits is so low, the rocking curves were scanned several times and the illustrated curves represent superimposed intensity data each collected over a several-day period. The base lines were established from intensity measurements well-removed from the central position. The low intensity precluded the observation of subsidiary maxima beyond the central peak. Since the curves can be represented reasonably as Gaussian distributions, the true diffraction half-width $W_D$ is expected to combine with the instrumental width $W_I$ to form the ob-

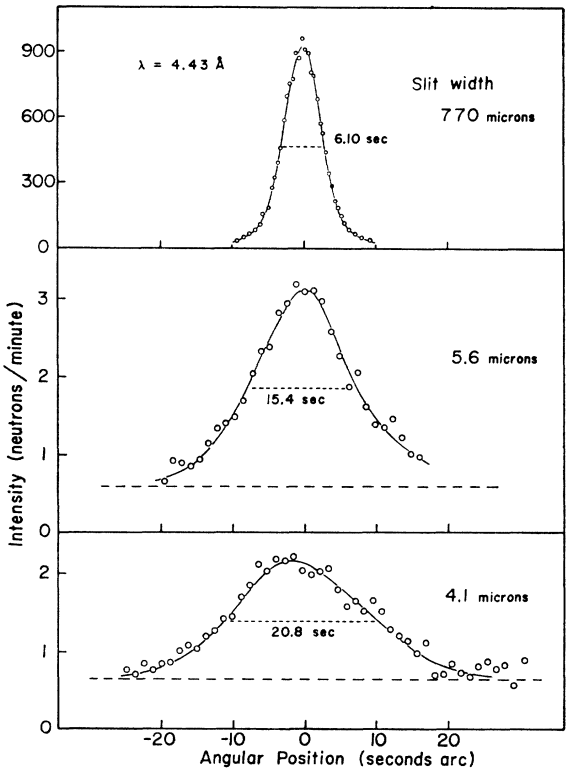


FIG. 2. Rocking curves of intensity versus angular position of the second crystal when slits of various widths are introduced between the two crystals of the double-crystal spectrometer. The measured half-width values are shown, with 6.10″ arc representing the instrumental resolution.

[3] C. G. Shull, R. Nathans, and H. Alperin, Acta Cryst. (to be published).

[4] It may be mentioned that this double-crystal spectrometer has been operated (see Ref. 3) with other crystal assemblies to yield much narrower instrumental width than used here. The present conditions represent a compromise between intensity and resolution.

served width $W_O$ as

$$W_O^2 = W_I^2 + W_D^2.$$

These values are summarized in Table I along with the expected half-width calculated from Eq. (1) using the mean of the two slit-width measurements. The agreement is within experimental uncertainty for all cases.

These Fraunhofer diffraction observations indicate that the neutron wavefront as it approaches the slit must be coherent over a transverse width at least that of the largest slit studied, namely 21 $\mu$. This is interesting when considered in light of the conclusions drawn from Pendellosung fringe observations reported separately,[5] where the coherence length of neutron wave packets was established as being at least 0.3 $\mu$. Thus the coherence volume of a neutron wave packet must be considered to be very extended relative to the de Broglie wavelength scale.

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[5] C. G. Shull, Phys. Rev. Letters **21**, 1585 (1968).

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# Interimpurity Recombinations Involving the Isoelectronic Trap Bismuth in Gallium Phosphide

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A new type of pair spectrum involving the radiative recombination of holes bound to Bi isoelectronic traps with electrons bound to remote shallow group-VI donors has been observed in GaP. The existence of these spectra proves that an isoelectronic impurity forms a stable trapping state for a single electronic particle. The binding energy of this state can be calculated from the positions of the pair spectra, and is $40\pm1$ meV for the Bi hole trap in GaP. The prominent phonon sidebands in the Bi-donor pair spectra and in the luminescence spectrum due to recombination from the $J=1$ Bi bound exciton state are similar, although the latter contains more detailed structure. The relatively large increase in the transition energy with decreasing pair separation $r$, characteristic of donor-acceptor pair spectra, is not observed in the Bi-donor pair spectra, where the first-order Coulomb interaction is zero because the Bi trap is neutral before the hole is captured. Instead, the Bi-donor pair transition energy *decreases* slightly with decreasing $r$ as a result of the electrostatic polarization interaction between the charged Bi trap and the neutral donor. The low-temperature time decay of both the Bi-donor and donor-acceptor pair spectra in GaP are slow and nonexponential, confirming that remote Bi-donor pairs of widely variable separation are involved. The decay time of the total luminescence is dramatically reduced, and the slow-decaying Bi-donor pair luminescence is quenched relative to the fast Bi-exciton luminescence, when the temperature is increased above $\sim$15°K. These changes are attributed to the phonon-assisted tunneling of electrons from the donors to Bi traps already filled by holes.

## I. INTRODUCTION

THE ability of isoelectronic impurities to produce bound exciton states was first recognized in GaP.[1] Only certain isoelectronic impurities can do this in a given semiconductor. For example, N [1] and Bi [2] atoms in GaP trap excitons with localization energies,[3] respectively, $\sim$11 and $\sim$97 meV. No bound exciton state occurs when some of the P atoms are replaced by As atoms, however. Bound exciton (B.E.) states associated with isoelectronic impurities have now been discovered in several different semiconductors, including ZnTe [4] and CdS.[5] Such states have not yet been reported for isoelectronic impurities on the cation

[1] D. G. Thomas, J. J. Hopfield, and C. J. Frosch, Phys. Rev. Letters **15**, 857 (1965).
[2] F. A. Trumbore, M. Gershenzon, and D. G. Thomas, Appl. Phys. Letters **9**, 4 (1966).
[3] The energy difference between the free and bound indirect exciton transitions.
[4] J. J. Hopfield, D. G. Thomas, and R. T. Lynch, Phys. Rev. Letters **17**, 312 (1966).
[5] A. C. Aten, J. H. Haanstra, and H. de Vies, Philips Res. Rept. **20**, 395 (1965); J. D. Cuthbert and D. G. Thomas, J. Appl. Phys. **39**, 1573 (1968).